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Title: *Acoustic and magnetic heating of chromospheres/coronae: are there distinct signatures?*

I. General

In a *qualitative* sense, the heating of chromospheres and coronae has long been ascribed to either acoustic or magnetic heating. However, *quantitative* discussions of the energy balance with detailed comparison to the fluxes of chromospheric emission lines have begun to appear only recently. The aim of this work is *to obtain more quantitative information on the acoustic/magnetic mechanisms by comparing data with models of acoustically heated atmospheres.*

Mechanical energy in acoustic form is *inevitably* present in all stars with convective envelopes. Once the acoustic waves are generated, their propagation and dissipation in the chromosphere and corona can be computed by *ab initio* models, again using the well defined equations of compressible hydrodynamics (e.g. Mullan and Cheng 1993,1994a,b: Papers I-III).

In contrast to the ubiquitous acoustic modes, magnetic modes need *not* be present. And even in stars where magnetic heating is at work, the atmospheric heating *always* includes an acoustic component as well. In order to evaluate the magnetic contribution in such stars, we need to separate out the acoustic contribution.

To address the "acoustic-magnetic" mixture, and separate the components, our strategy in this work has been to select stars in those parts of the HR diagram where the magnetic contribution is "turning on". By studying such stars, we hope to quantify the acoustic component which pervades the atmospheres of all cool stars, and characterize how the magnetic components alter the emission measure distribution in the atmosphere.

Two groups of stars are suitable for our purposes: they are the groups which have recently been the subject of detailed quantitative modelling as regards acoustic propagation, i.e. the coolest dwarfs and the warm stars.

II. Results obtained for the coolest dwarfs: dM and dMe

Among the M dwarfs, the dMe stars (most of which are flare stars) have Hα in emission while the dM stars (only a few of which show flares) have Hα in absorption. It is likely that dMe star atmospheres are heated predominantly by the magnetic fields which create their flares. On the other hand the dM stars are less active, although by no means lacking in chromospheric heating (Cram & Mullan 1979; Doyle et al. 1994). The coronae in dMe stars contain two components, a hot one at temperatures of 10^7 K and more, and a cool one with T close to 10^6 K (Giampapa et al. 1996). The temperature of the hot component is of the same order as flare-heated plasma, and this component is variable: it therefore might be magnetic in nature. On the other hand, the cooler material has a temperature close to that predicted for acoustically heated coronae (Paper II), and its lack of temporal variability is a property which would be consistent of acoustic heating (since the convective flow patterns are essentially always present).

To make this distinction more quantitative, we have recently analyzed the ROSAT data using X-ray surface fluxes, F_X (Mullan and Fleming 1996: reprint attached with this report). The dMe stars have an F_X distribution which is clearly distinct from that of dM stars (see Fig. 2 in the attached paper). The observed F_X is a superposition of quiet regions with flux F_q occupying a fractional area $1 - f$ and active regions with flux $R_{mq}F_q$ (R_{mq} is the ratio of magnetic to quiet fluxes) occupying fractional area f. Using solar values of $R_{mq} \approx$ 20-50 as a guide, we can extract from any particular star a value of F_q once a value is assigned to f. We ask the question: *do quiet regions in dMe stars emit the same F_q as quiet regions in dM stars?* To address this, we assign random values of f to each dM star and random values of f to each dMe star in the 6-7 pc sample and extract a distribution of F_q for dM and dMe stars. We then apply the Kolmogoroff-Smirnov (KS) test to these distributions to determine if they are ever "similar" in a statistical sense. We find that indeed, the F_q distributions turn out to be similar provided that the mean fractional area of active regions is large (0.8-0.95) in dMe stars and small (0.03-0.08) in dM stars. This is consistent with the expectation that dM stars have very few active regions, whereas dMe stars are almost entirely covered with active regions. One particular solution is shown in Fig. 4 of the attached paper, where we show the F_q distribution for dM stars (solid) and dMe stars (dotted). The two distributions are indistinguishable according to the KS statistic. The vertical dashed line in the figure indicates a theoretical upper limit on X-ray fluxes from acoustically heated coronae in M dwarfs (Paper II). This limit (which was computed before the ROSAT data were available) may provide a sort of upper bound on the F_q distributions.

These results suggest that it is consistent to interpret *coronal heating in quiet regions in dM and dMe stars as acoustic in nature.* Moreover, the temperature of the cooler (time-invariant) component is comparable to the upper limit on temperature predicted in an acoustically heated model (Paper II).

Summarizing the data for the 6-7 pc M star sample, we may say that ROSAT provides some quantitative information which hints at a separation between acoustic and magnetic heating. However, the energy resolution of the ROSAT data is rather poor. The PSPC spectra can be fitted by 2-T solutions, but it is essentially impossible to extract multi-temperature fits.

For that reason, we now turn to EUVE data.

III. Warm stars: chromospheres and coronae

Evidence for chromospheres and coronae in warm stars (spectral classes A and F) comes from the CII 1335 line and X-rays: both have been detected in stars as early as A7 (Simon et al. 1994; Walter et al. 1995). The X-rays are rather soft $T \leq 10^6$ K (Golub et al. 1983). Moreover, several F stars appear in the ROSAT/WFC catalog (Pounds et al. 1993) and in the EUVE all-sky survey (Malina et al. 1993; Bowyer et al. 1994). The non-magnetic nature of heating in stars of spectral type A to early F is suggested by the lack of rotation-activity connection (Walter 1983): e.g. Altair's X-ray emission is highly constant (J. Schmitt, pers. comm.). EUV filter ratios for A stars suggest temperatures of 10^{5-6} K, consistent with acoustic heating (Paper III).

Warm stars are much stronger acoustic sources than the Sun. To see this, note that vigorous convection occurs in A and F stars, as proven by large microturbulence ξ (Coupry and Burkhart 1992) and large amplitude of the C-shaped bisectors of spectral lines: both are indicators of convection (Nordlund 1980; Gray 1992). Since acoustic energy generation rates are very sensitive to ξ ($\sim \xi^8$), acoustic generation is highly efficient in A and F stars.

The shape of the DEM contains information on the energy balance in the atmosphere (Jordan 1980). Predictions of the distribution of emission measure (DEM) as a function of temperature in an acoustically heated F star have been published (Paper III). In the case of the F5 star Procyon, the DEM predictions included a minimum at $\log T_m = 5.4$, with steep slopes on either side of this minimum: in a subsequent analysis of EUVE data, Drake et al. (1995) found that the predictions provide an "impressive" fit to their data.

The present study is aimed at evaluating DEM in various warm stars in order to examine the energy balance.

III.1 Warm stars: EUVE analysis

We have developed a code for efficient analysis of line fluxes in EUVE spectra. Line fluxes are extracted from archival data tapes using standard IRAF/EUV software. In order to determine which lines in the spectrum are above the noise, we also extract a "spectrum" of the background in the EUVE image by scanning across the image at a position well removed from the stellar photons. We process this background "spectrum" in exactly the same way as we do the actual stellar spectrum, and extract "line fluxes" for all the features in the 'spectrum". We fit these "background line fluxes" as a function of wavelength using a least squares technique to a Chebyshev series: we increase the length of the series until we reach a point where the fit is numerically independent of a linear combination of Chebyshev polynomials. In order to accept a line in the stellar spectrum as "real", we require that the flux in that line exceed 3 times the value of the best fitting curve to the "background line fluxes".

The fluxes of the accepted lines are converted to stellar surface values. To correct for interstellar absorption, we use a tool provided by the EUVE archives: the ISM hydrogen column density table. To use this, we insert the position of the star in question, and its distance, and the program responds with a list of the ten stars which are nearest (in space) to the target star for which column densities N_H are available in the literature. For each extracted line, we enter the Landini and Monsignori-Fossi (1990: LMF) table of line emissivities and search for possible line identifications within the nominal uncertainties of the EUVE wavelength scale (± 0.5, ± 1.0, and ± 2.0 A for short, medium, and long wave spectrometer respectively). Possible lines in these ranges are arranged in order to peak emissivity: those which lie within a factor of 3 of the maximum emissivity are assumed to contribute to the observed line, with a contribution proportional to the emissivity. This is clearly not as precise as the process of individual profile fitting which has been described by (e.g. Drake et al. 1995). However, our work is aimed at stars where the lines are weak, and close to noise level. Thus, a more sophisticated approach to line-fitting is not warranted for these faint lines. Moreover, our approach is more automated, and can be applied to a broad class of targets.

The LDF emissivity tables are listed in intervals of 0.1 in $\log_{10}$ T. The flux of each identified line is converted to an emission measure as if emissivity were constant over ± 0.05 on either side of the tabulated $\log_{10}$ T. In this sense, the output can be thought of as proportional to the emission measure integrated over a certain interval $\Delta \log_{10} T = 0.43 \Delta T/T = 0.1$.

We group the lines according to stage of ionization: if two or more lines of a given stage of ionization are found to have DEM within a factor of ± 2 of their mean, we classify them as "good lines". The "leftover" lines are grouped according to temperature, and mean DEM are constructed at each temperature: the r.m.s. deviations σ of these means for the "leftover" lines are distinctly larger than those for the "good lines". Weights are assigned to the DEM in both "good lines " and "leftover" samples according to $1/(\sigma^2)$. Regression analysis is used to obtain the best fit of a series of Chebyshev polynomials to the DEM. The quality of fit is assessed by the mean separation between the fitted curve and each point, expressed in units of the r.m.s. deviation of each point: this provides a sort of reduced χ^2 (RCS) for the fit.

Our code is meant mainly to be used on faint targets where the spectrum is close to the noise level. But to test the code, we also run it on stars where the spectrum is well above background. One example is Procyon. We discuss this star first.

III. 2. Procyon in EUVE: comparison with the Sun

Results for Procyon are shown in Fig. 1. Our "goodlines" are plotted as filled squares with error bars, while the "leftover" lines are open squares. The weighted least squares fit is shown by the solid line: at the lowest temperatures, there is a region with a steep negative slope. Then there is a minimum at log T = 5.5-5.6 followed by a rise to a maximum at log T = 6.5-6.6.

How well do our results agree with earlier more detailed work on Procyon? The dashed line shows the results obtained by Drake et al. (1995): their curve overlaps ours, and shows a minimum at log T $\approx$ 5.5, and a maximum at log $T \approx$ 6.3-6.4. The values of DEM at minimum and maximum agree with ours within ± 0.2 and $\pm$ 0.3 in the log. Since we have accepted "goodlines" as those which have DEM within a factor of 2 of each other (i.e. within 0.3 in the log), the quantitative agreement between our work and that of Drake et al. (1995) is satisfactory. The predictions of acoustic heating (short dashed line: Paper III) overlap with our best fit curve, although the minimum is deeper than our results indicate: however, this may be due to our limited resolution in temperature.

For comparison with solar data, we indicate results for Quiet Sun and Active Region by the curves labelled QS and AR: these are taken from Brosius et al. 1996. The quiet sun data were obtained in 1993, and the active region data in 1991. Brosius et al. give DEM's in units of cm^{-5} K^{-1}: therefore, to convert to our integrated EM, which corresponds to $\Delta T = 0.23T$, we multiply each of the values given by Brosius et al. by the local value of $0.23T$. The results are shown by the dash-dot and dash-double dot lines labelled QS and AR. Comparison between solar and procyon data suggests that Procyon contains material which is as hot as, or hotter than, the material in solar active regions: in fact the Procyon DEM has a maximum at a temperature which is identical (within our resolution) to that where the AR curve peaks (log $T = 6.6$). Moreover, the AR curve overlaps the error bars of some of the Procyon "goodlines", suggesting that even the quantity of material at 3-4 MK in Procyon is comparable to that in the solar active region. This supports the claims made by Jordan and Brown (1986) and by Drake et al. (1993) that in order to understand data obtained by in ultraviolet, X-ray, and radio obaervstions, there must be active regions and/or non-thermal sources of emission on Procyon. However, at intermediate temperatures, (log T = 5.3-6), the atmosphere of Procyon contains much 1-2 orders of magnitude more material than the solar active region: we note that the dotted line labelled "Acous" in the Figure provides a better fit to the material at intermediate temperatures. This curve was obtained in Paper III, and is based on the high level of emission of acoustic power from the F5 convective zone.

Thus, Procyon may be an example of a star where both acoustic heating and magnetic heating (i.e. active regions) can be identified by our techinque.

III.3. Altair in EUVE: comparison with the Sun

For Altair, as far as we know, the DEM for this star has not previously been published, although the existence of a weak chromosphere and corona has been known (Walter et al. 1995). The results of our analysis are shown in Fig. 2. Again, "goodlines" are plotted using filled squares, while "leftover" lines are plotted as open squares. the solid curve is the least squares best fit to a Chebyshev series. The results show some important differences from those for Procyon (for which the Drake et al. [1995] curve is plotted as the dashed line labelled Pr). First of all, Altair is a very weak source in EUVE. Because of the weakness of the source, and the poor signal to noise ratio, it is important to have a non-subjective method for identifying "real" lines in the spectra. Only 7 "goodlines" merged from our processing (as opposed to 130 for Procyon), and 41 "leftover" lines with lower confidence in the identifications.

In our best fit solution, we find a cool peak (at log $T \approx 5.2$), a minimum at log $T = 5.8$-5.9, and a hot peak at log $T \approx 6.3$. Since the lines in the spectra are so close to the noise level, it is important to ask: are our results physically meaningful? To answer that, let us see if the distribution can reproduce the X-ray flux observed by ROSAT: 8.8×10^{-13} ergs cm^{-2} sec^{-1} (cgs) over the energy range 0.15-2.3 keV (Walter et al. 1995). In order to estimate what the X-ray flux would be from our distribution, let us approximate the distribution by an isothermal plasma at log $T = 6.3$ and an emission measure EM = 10^{51} cm^{-3}. Using numerical values given by Drake (1970), we note that an isothermal plasma at temperature T_6 MK at the distance of the Sun creates a flux of $10^{-51} EM sqrt T_6 e^{-1.75/T_6}$ cgs at Earth. Thus, the above plasma (with $T_6 = 2$) would produce a flux of 0.6 cgs at Earth. At the distance of Altair (5.2 parsec = 1.07×10^6 AU) the measured flux would be 5×10^{-13} cgs. This is within a factor of 2 of the observed X-ray flux. This suggests that despite the weak lines in the Altair spectrum, we are measuring physically realistic fluxes.

At the lower temperatures (log $T \leq 5.6$), the DEM of Altair rises well above the Procyon values: the excess is one order of magnitude or more. Now, acoustic heating leads to rapid increase in DEM towards the lowest temperatures: see the dotted curve in Fig. 2 labelled "Acous.", which was obtained for the Procyon atmosphere with a certain input flux of mechanical energy (2×10^7 cgs: Paper III). However, in an A7 main sequence star (with log $T_{eff} = 3.9$), the acoustic fluxes are expected to be larger than in Procyon (log $T_{eff} = 3.8$) by a factor of about 10: the fluxes scale as $T^{9.75}$ (Bohn 1984). In fact, on the main sequence, A7 stars such as Altair should have close to the maximum acoustic emission. Thus, the high level of DEM in the gas at log $T = 5.2$-5.5 in Altair is consistent with acoustic heating.

A striking feature in the Altair DEM is the sharp cut-off in the DEM at temperatures in excess of log $T = 6.5$: this is quite different from the behavior in Procyon, and also different from the behavior of the solar active region. On the other hand, the Quiet Sun has a DEM which peaks at a temperature close to the Altair peak. This suggests that the outer atmosphere of Altair is more similar to quiet Sun than to Active regions. This may mean either (a) Altair has no active regions, or (b) if there are active regions, they are too small to contribute significantly to the EUVE spectra.

III.4. Overview of other warm stars

We have applied the same technique to EUVE spectra of all of the other A-F stars in the EUVE spectral data base which are not contaminated by white dwarf continua: there are four such stars, namely, 71 Tau (F0), HR120 (F2), HR1817 (F7: two spectra), Upsilon Peg (F8IV). We also applied the technique to the star AY Cet (G5III) which is somewhat cooler than our "warm" star sample, but which has a spectrum which is also close to the noise level, and is therefore a test of the analysis technique which we use. The reason for analyzing two HR1817 spectra (rather than summing them) was that some spectral lines underwent noticeable changes in flux from one exposure to the other, as if a flare had occurred.

Although we could go into detail about each spectrum, it it serves our purposes here better to present an overview of all 8 spectra which we have analyzed. The weighted best fitting

Chebyshev polynomial series for each of these 8 is presented in Fig. 3. All of the data have been plotted on the same scale. The two lowest lying curves are recognizable from Figs. 1 and 2: they belong to Altair and Procyon. The levels of mechanical heating in the atmospheres of these two stars are lower than in any other stars in the sample.

The only G star in the sample (AY Cet) distinguishes itself by lying well above the other curves in the intermediate range of temperatures log T = 5.5-6.5: however this is the only giant star in the group, and so the large values of emission measure may be due in part to the large surface area of the star.

The remaining 5 spectra of F stars have DEM's which cluster close to one another at intermediate temperatures, but at higher temperatures there are distinct behaviors. Two of them have a broad peak in the DEM at log T = 6.7-6.8: these are HR1817 (spectrum No. 1) and Upsilon Peg. These stars are similar in spectral type (F7, F8), and their high-T peak resembles that in Procyon (F5), although at an amplitude of 100 times larger. Could this be evidence for active regions also in HR1817 and Upsilon peg? The second spectrum of HR1817 has a very hot peak at log T = 7.1-7.2, similar to solar flares: this is consistent with the obvious change in certain line strengths between exposure 1 and 2 in this star. Flares suggest magnetic activity, and this supports the presence of active regions in this star. Very hot peaks are also present in the two earliest F stars in the sample: 71 Tau (F0) and HR 120 (F2). The peak in 71 Tau is especially striking. There are not enough data to decide whether this peak arises from flaring activity in these two early F stars.

To check on the possibility of flaring, we also include in Fig. 3 some results obtained from a different satellite (GOES): this satellite records the X-ray intensity of the Sun in two X-ray bands with wavelengths of a few A, i.e. much higher in energy than the EUVE range. Ratios of the fluxes in the two bands lead to estimates of the temperature in the flaring plasma. This one-temperature fit to the plasma emission is a much cruder characterization of the plasma properties than what can be obtained from spectral data (such as EUVE), but it allows one to describe the statistics of solar flares in a simple way. The emission measures and temperatures obtained from a large sample of *solar flares* (Feldman et al. 1996) are plotted by the dotted line labelled SF(1-T). The temperatures are hotter than those which can be reliably identified in EUVE data, and so we cannot make a detailed comparison between the solar flarers and the EUVE data. But the flare data are suggestive of the possibility that some of the larger EM values at the hotter temperatures (especially in 71 Tau) might be flare-related.

IV. What has been learned from ROSAT and EUVE

ROSAT data on M dwarfs suggests that we may have identified acoustically heated portions of the coronae in M dwarfs. If this can be confirmed, it would represent a paradigm shift: in the Sun, there appears to be very little (if any) acoustic heating of the corona, and this has colored the approach to coronal heating in other stars. In M dwarfs, physical conditions are sufficiently different from those in the Sun that what applies to the Sun does not inevitably also apply to the M dwarfs.

From EUVE, we have found that the emission measures of hot material in F star atmospheres varies over sevreal orders of magnitude. The overview of our results in Fig. 3 shows this clearly. Moreover, we have managed to obtain a DEM for an A star for the first time (Altair A7): the DEM is strikingly different from that of the F stars in the sense that Altair contains no material hotter than 2-3 MK: the cutoff of the DEM at log T = 6.5 in Altair is quite sharp. Clearly, it would be very valuable if we could get access to another A star with EUVE: Alpha Cep is such a star, with spectral type A7 (Walter et al. 1995), but it is fainter than Altair by a factor of 4-5 in the optical, and by a factor of 9-10 in X-rays, and so may be too close to the background level of EUVE. There is one star in the EUVE spectral archives labelled as A8m (HR8210): but it has a white dwarf companion, and this continuum will have to be removed before we can apply our analysis. In view of the importance of finding another A star in EUVE, we have requested assistance from Dr J. Dupuis (CEA) to remove the white dwarf continuum from HR8210.

The overview in Fig. 3 also shows that the *slope* of the DEM in the temperature range from minimum EM to maximum EM varies widely: if we parametrize EM$\sim T^b$, we find that b varies from as small as 1 (Procyon) to 1.5 (ups) to 2 (AY, 1817) to 3.5 (Altair) to almost 10 (71 Tau). The slope contains information on the energy balance of the atmosphere (Jordan 1980; Raymond and Doyle 1981): in the Sun, the slope is often regarded as having the value 1.5, but in fact b varies from values as small as 0.9 ± 0.15 in network in a coronal hole to as large as 3.1 in active regions and flares. Further analysis of the different slopes which we have found in the DEM curves of F stars may help to elucidate some of the energetics of the heating process.

Our sample of 8 spectra is too small to decide yet how general our results are, but it appears encouraging that we might be able to distinguish heating mechanisms from the DEM distributions.

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Figure captions

Fig. 1. DEM for Procyon. Abscissa: log of temperature (degrees K). Ordinate: log of emission measure in units of cm^{-3}. Filled squares: "good lines"; open squares: "leftover lines". Solid line: weighted best fit of Chebyshev series to log (DEM) versus log T. Long dashed line: results from Drake et al. 1995. Short dashed line: acoustic heating (paper III). Dash-dot line and dash-double dot line: Quiet Sun (QS) and Active Region (AR) results from Brosius et al. 1996.

Fig. 2. DEM for Altair. For notation, see caption of Fig. 1.

Fig. 3. DEM for 8 EUVE spectra. The curves are weighted best fits of Chebyshev series to log (DEM) versus log T.

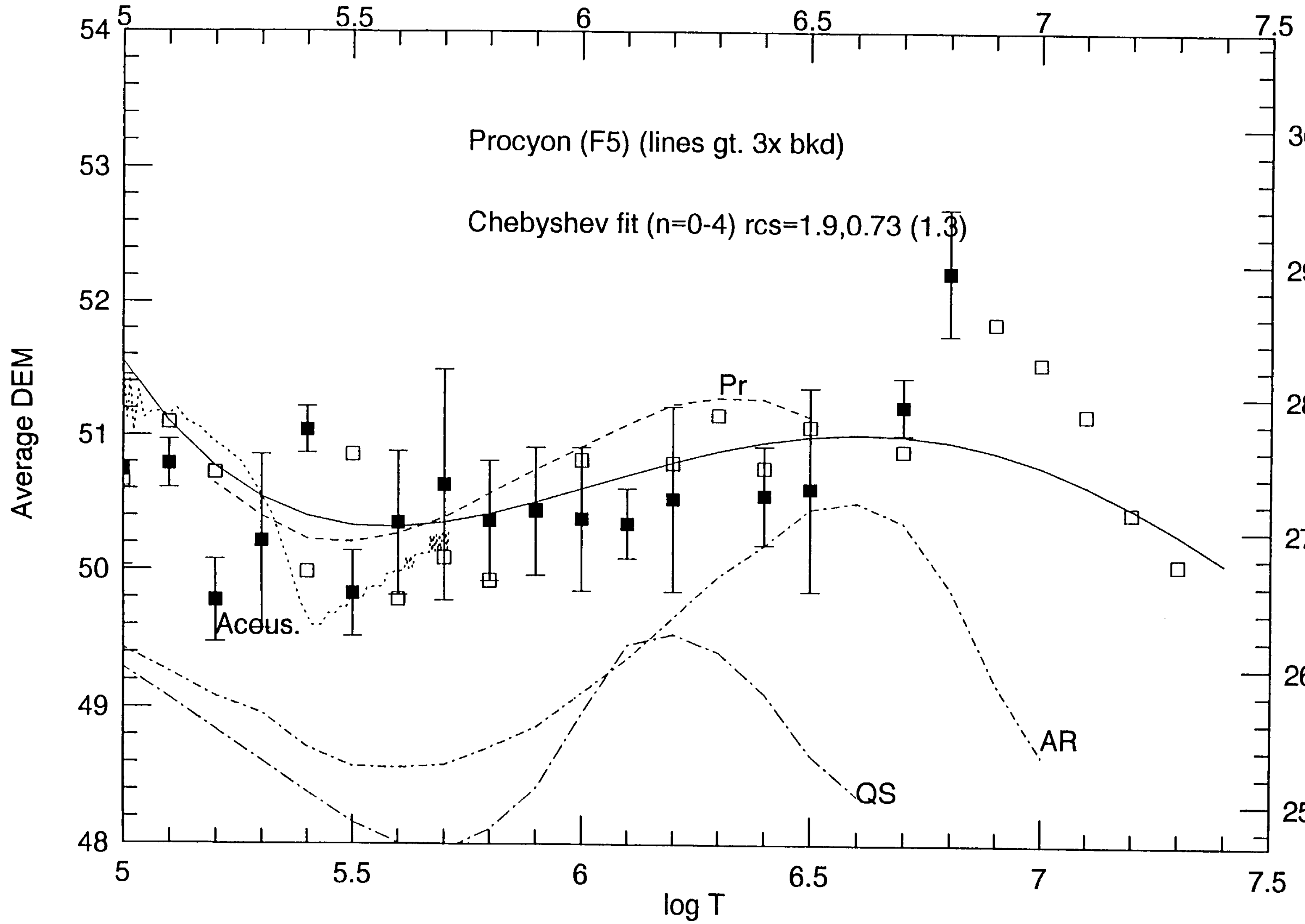

Procyon (F5) (lines gt. 3x bkd)
Chebyshev fit (n=0-4) rcs=1.9,0.73 (1.3)
Average DEM
log T
Pr
Acous.
AR
QS

FIG. 1

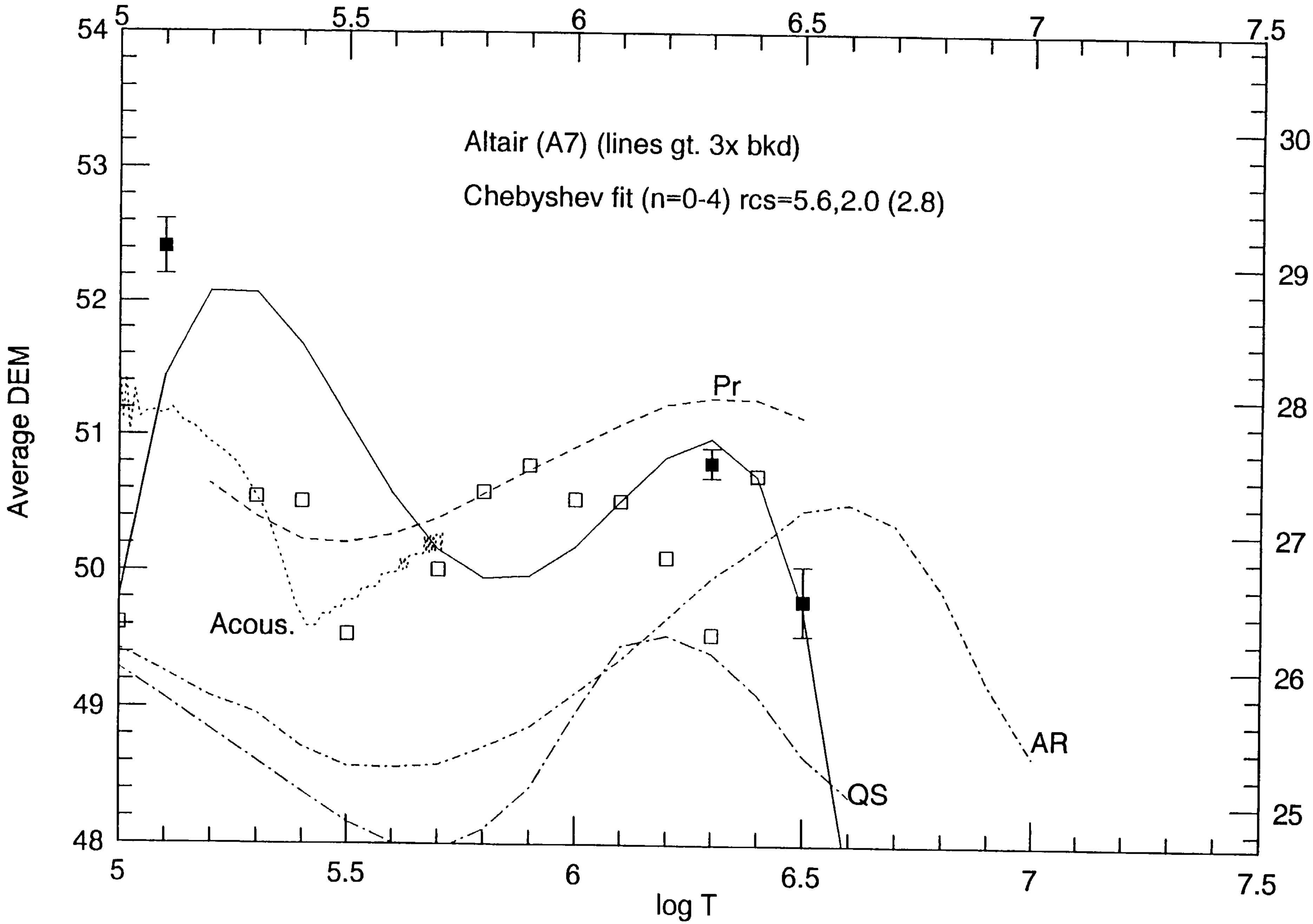
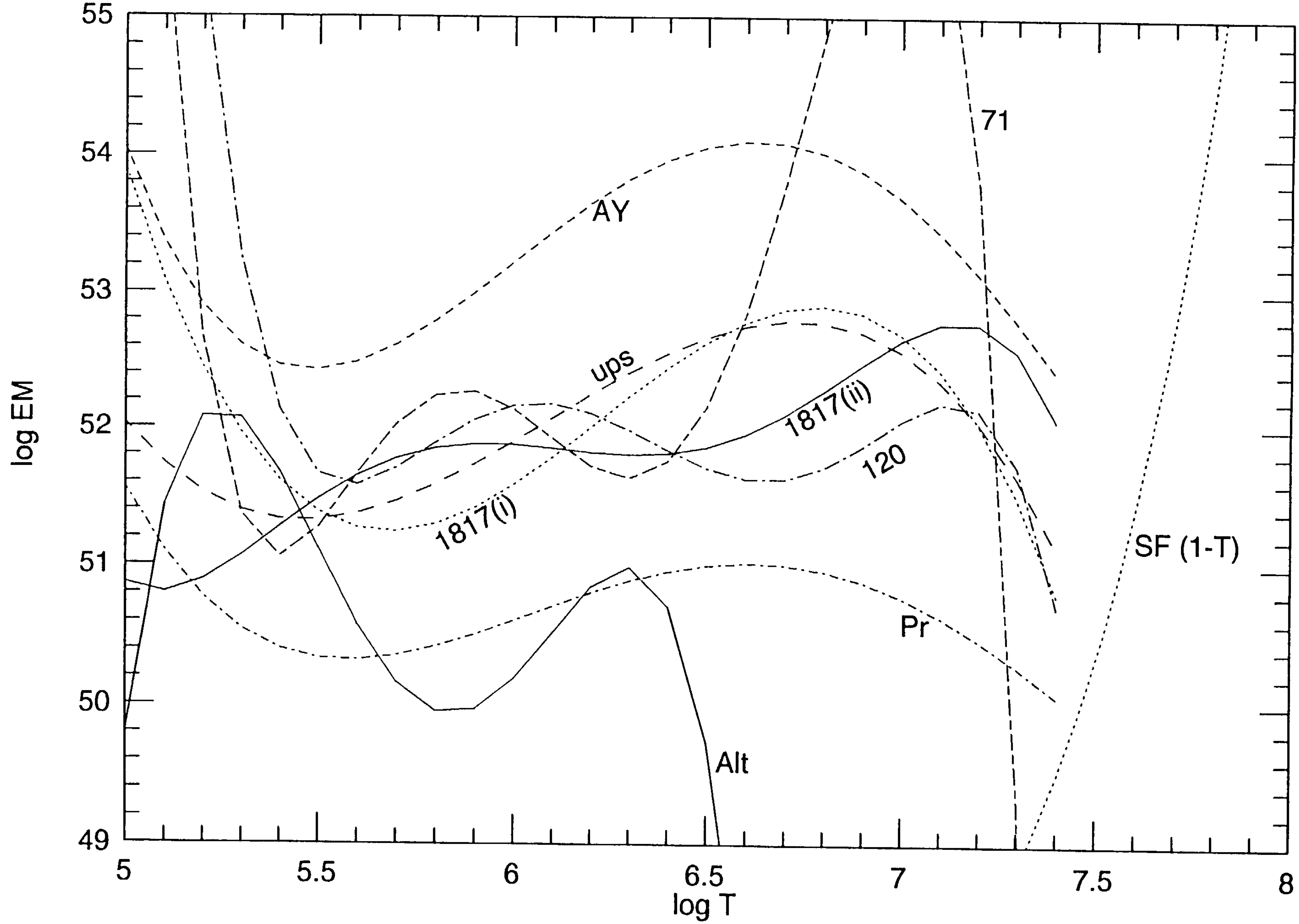

Altair (A7) (lines gt. 3x bkd)
Chebyshev fit (n=0-4) rcs=5.6,2.0 (2.8)
Average DEM
log T
Pr
Acous.
AR
QS
54
53
52
51
50
49
48
5
5.5
6
6.5
7
7.5
30
29
28
27
26
25

FIG 2



55
54
53
52
51
50
49
log EM
5
5.5
6
6.5
7
7.5
8
log T
AY
ups
1817(i)
1817(ii)
120
71
Pr
Alt
SF (1-T)

FIG 3